







The Moon is a Planet Too: Lunar Science and Robotic Exploration

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U.S. Space Policy (VSE)

- Conceived in response to loss of Columbia Shuttle, 2003
 - Return Shuttle to flight
 - Complete ISS assembly and retire Shuttle
 - Build new human spacecraft for transport beyond LEO
 - Return to the Moon with people and robots to explore and prepare for voyages beyond
 - Human missions to Mars and other destinations
- Proposed by President Bush, endorsed by 109th Congress, now national policy


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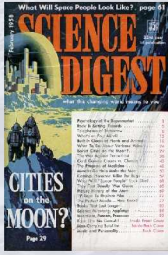
Wait – haven't we been there, done that?

- Yes, we've been there – but we haven't done that!


Lunar Exploration
We'll learn to
live and work on
another planet



Lunar Science
The Moon is a
window back in time
to understand how
all rocky worlds
formed and evolved



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Going back to the Moon for science

- Lunar science through Apollo 17 told us about commonality of planets and uniqueness of the Moon
- Now we have many questions about how planets work that can be answered on the Moon
- We know more about Mars than we do about the Moon in some ways!

	Mars	Moon
Best orbital resolution	2 cm/px (HiRISE camera on Mars Reconnaissance Orbiter, 2005)	50 cm/px (LROC camera on Lunar Reconnaissance Orbiter, 2009)
Topography and Gravity	37 cm vertical, 330 m horizontal (MOLA on Mars Global Surveyor, 1999)	100 cm vertical, 100 m horizontal (LOLA on Lunar Reconnaissance Orbiter, 2009)
Robotic rovers	Pathfinder, Spirit, Opportunity, MSL	Russian Lunakhod-1 and Lunakhod-2
Landing site coverage	Global (east/west, equatorial/polar)	Limited (nearside equatorial only)


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The Moon is a terrestrial planet

- The Moon holds a unique place in the evolution of rocky worlds - many fundamental concepts of planetary evolution were developed using the Moon
- The Moon today presents a record of geologic processes of early planetary evolution:
 - The Moon and Earth are related and formed from a common reservoir
 - Lunar interior retains a record of the initial stages of planetary evolution
 - Lunar crust preserves ancient crater record, unaltered by plate tectonics (Earth), planetwide volcanism (Venus), or wind and water (Mars & Earth)
 - Surface exposed to billions of years of interplanetary inputs

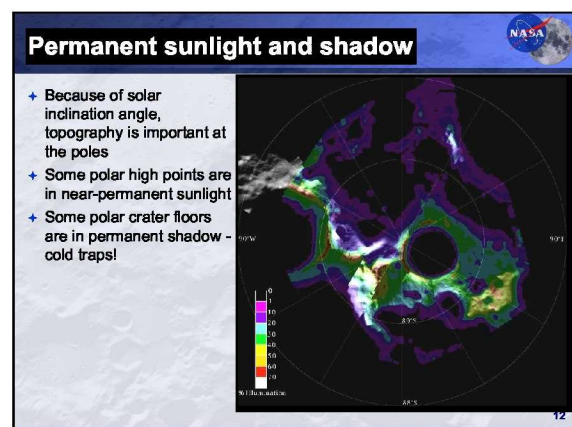
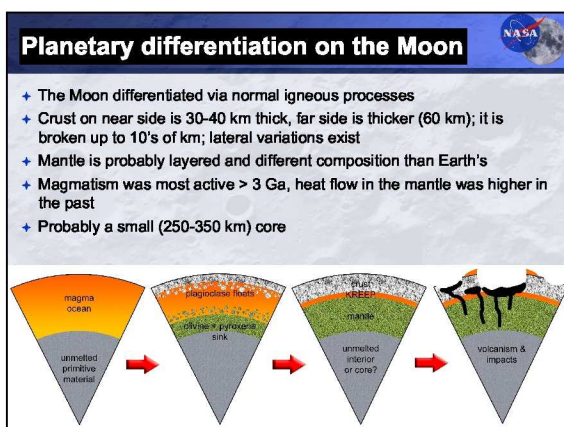
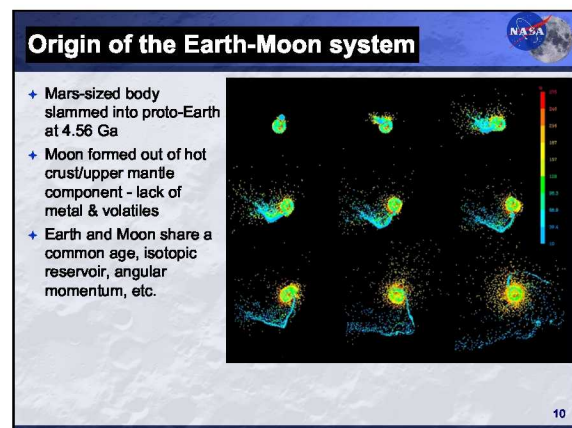
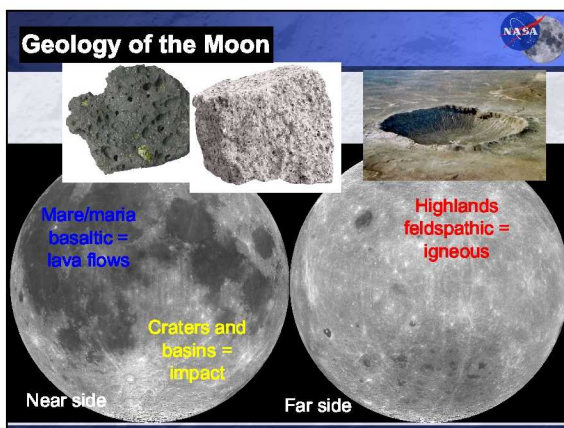
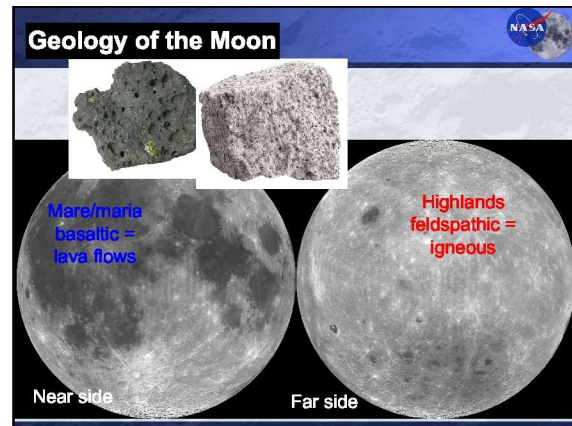
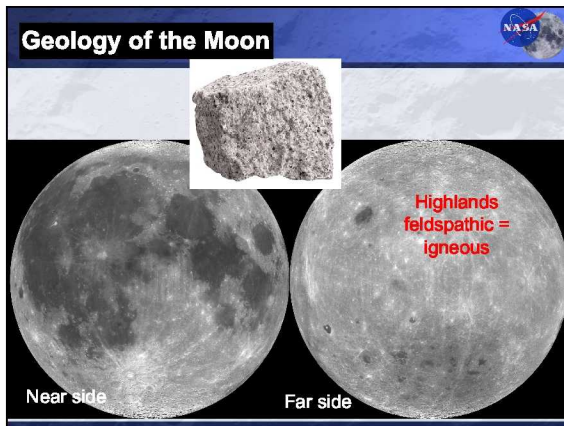
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Geology of the Moon



Near side Far side



Lunar atmosphere and cold traps

- Surface-bound exosphere, common to airless bodies
 - Ne, He, H from the solar wind
 - Ar outgassing from lunar interior (decay of K)
 - Na, K, ballistic particles liberated from silicates
 - H₂O, CO₂, CH₄, NH₃ from exogeneous sources (comets & asteroids)
- Clementine and LCROSS will measure water content

A free surface in interplanetary space

- The lunar surface interacts directly with the interplanetary environment
- Records the current and ancient plasma environment, solar wind, micrometeoroid flux, magnetic fields, etc.

Crater diameter (μm)	Number (m ⁻² yr ⁻¹)
≥ 1000	0.001
≥ 100	0.6
≥ 10	300
≥ 1	1200
≥ 0.1	30000

	Energy (MeV/nucleon)	Flux (cm ⁻² s ⁻¹)	Penetration depth (cm of Al)	Max dose
Solar wind	10 ⁻³	10 ⁸	10 ⁻⁴	0
Solar energetic particles				
Protons	1 to 10 ³	<10 ⁴	1 to 10 ²	<10 Gy
Helium nuclei	1 to 10 ³	~1%	1 to 10 ²	~1%
Galactic cosmic radiation				
Protons	10 ² to 10 ⁴	2	1 to 10 ⁴	0.02 Sv/yr
Heavy nuclei	10 ² to 10 ⁴	0.2	10 ¹ to 10 ⁴	0.23 Sv/yr

Craters of the Moon

- The Moon is the only place that links relative ages (crater counting) with absolute ages (samples)
- Forms the basis for all other surfaces (Mars, Mercury, etc)
- Bombardment history of the Moon is magnified on the Earth

The Lunar Cataclysm Hypothesis

- An anomalous period of increased bombardment around 3.9 Ga – 600 Myr after solar system formation
- A post-Apollo view of a dynamic solar system
 - Precise ages of impact-melt samples
 - Large numerical simulations of planet formation & migration
- Catastrophe** – 1,700 craters on the Moon / 22,000 impact craters on the Earth
- Catalyst** – delivery of 1023 g of asteroidal/cometary material to the Earth, including C, H₂O, and reduced species
- Cauldron** – impact-generated hydrothermal systems may be niches
- Crucible** – extreme environments affect evolutionary paths

Impact craters

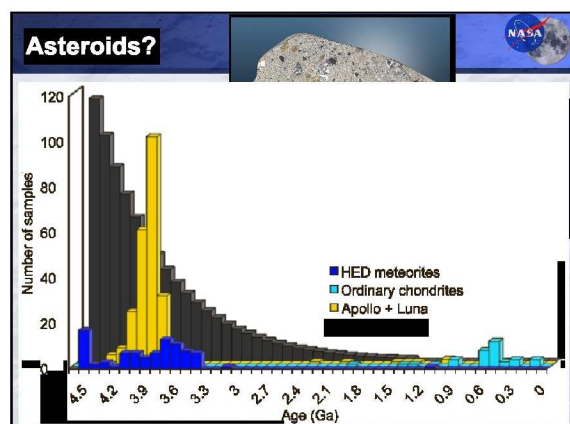
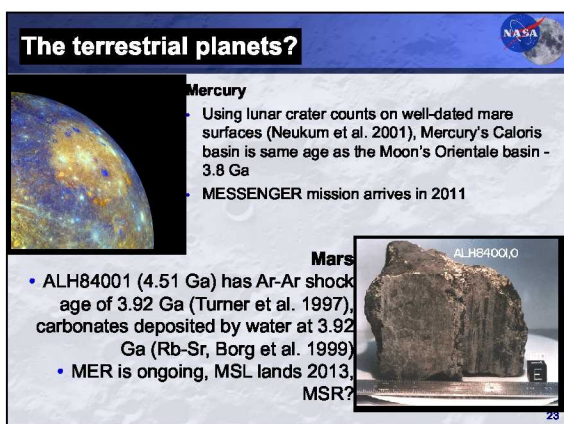
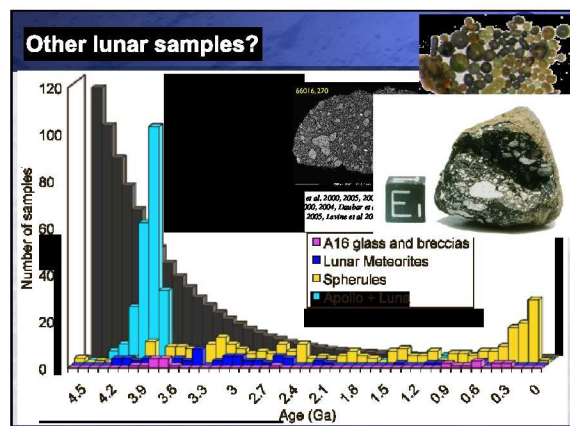
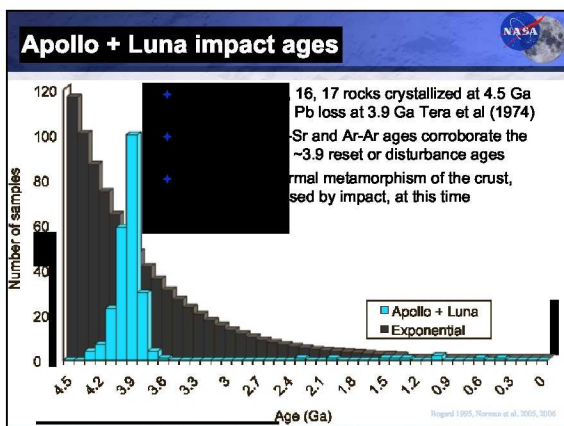
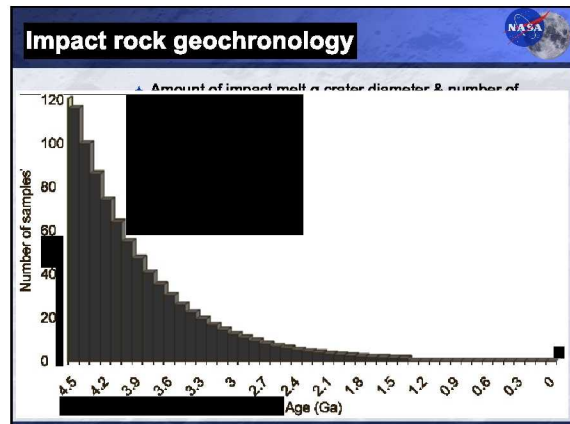
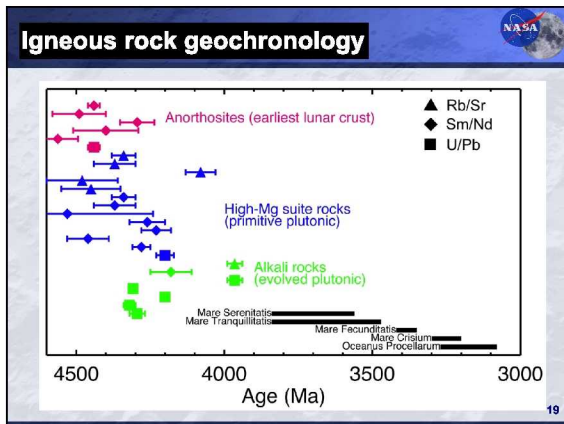
- Impact process is most akin to an explosion
- Impactor is vaporized, target is shocked

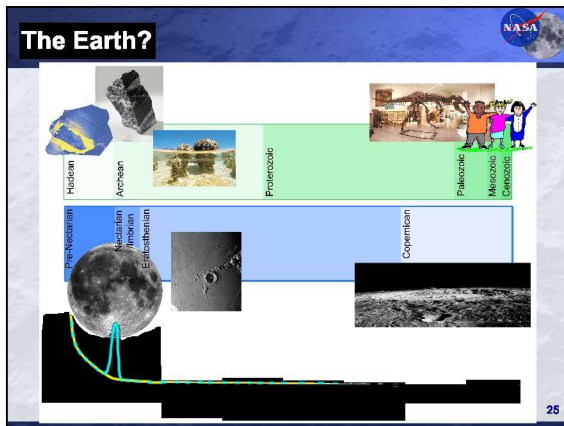
Sedan
 104 kTon
 D=0.4 km
 Energy = 1/2 mv²
 v = 11 km/s
 for a 10-km rock,
 m = 10¹⁵ kg
 E = 10²³ J
 or
 10⁷ Megatons TNT!

Barringer
 2.5 MTon
 D=1.2 km

Impact melt rocks

- Geologic association with specific craters and basins
- Form distinct groups in composition, texture, petrology
- Reflect distinct impactor composition that formed them



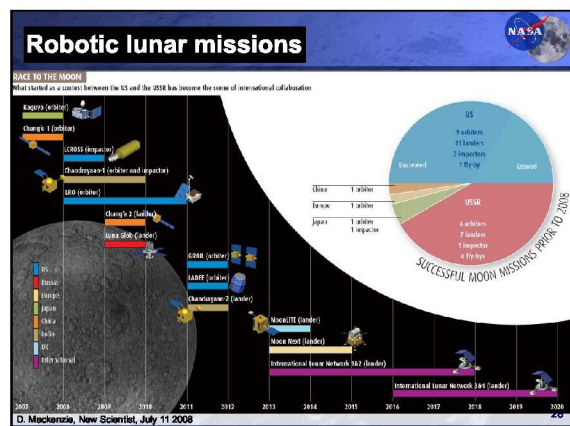


A dynamic early solar system

- Total mass necessary to create late lunar basins 10^{21} - 10^{22} g
- Solar-system accretional leftover sweepup is rapid (100 Myr) (Morbidelli et al. 2001) and requires total leftover masses of 10^{23} - 10^{28} g (i.e. masses of Vesta & Earth)
- Earth-Moon debris sweepup is also rapid, doesn't hit all inner planets
- Asteroid breakup (Zappala et al. 1998) requires Ceres-sized body breakup, dynamically unlikely at 3.9 Ga, no family observed
- Jupiter & Saturn migration (Levison et al. 2001, 2005; Gomes et al. 2007) scatters icy planetesimals, resonances sweep through main belt
- 5th terrestrial planet (Chambers et al. 2002) between Mars and main belt becomes unstable after 600 Myr, scatters asteroids & hits the sun
- Close brush with another galaxy or massive object?
- *The early solar system was a dynamic, violent place to be!*

A Lunar Cataclysm...?

- Impact-melt sample groups tied to individual impact events based on major, minor, and trace elements, geologic interpretation
- Multiple different impact-melt groups from the Apollo landing sites are 3.9 Ga, tied to **5 large basins** plus other craters?
- Diverse approaches to further testing exist and are an opportunity for both the planetary and terrestrial communities
 - Understand sample ages and sample bias on planetary surfaces
 - Differences between the lunar surface and other locations
 - 3-D regolith modeling
- Pin down one large, old basin age – SPA Sample Return Mission



LRO Mission Overview

- On-board propulsion system used to capture at the Moon, insert into and maintain 50 km mean altitude circular polar reconnaissance orbit
- 1 year exploration mission followed by handover to NASA science mission directorate

Lunar Orbit Insertion Sequence

Commissioning Phase, 30 x 216 km Altitude Quasi-Frozen Orbit, Up to 60 Days

Polar Mapping Phase, 50 km Altitude Circular Orbit, At least 1 Year

LCROSS (2009)

- Lunar Crater Observation and Sensing Satellite, secondary payload on LRO vehicle, Ames project under LPRP management at MSFC
- Will use the expended LRO Centaur upper stage as an impactor and observe the plume

LCROSS Objectives:

- Confirm the presence or absence of water ice at a lunar pole
- Create an ejecta plume and analyze it for the presence of water (ice and vapor), hydrocarbons and hydrated materials

LCROSS Mission Overview

- About equal to 1.5 tons of TNT, excavating 200T lunar rock and soil
- Crater estimated to have ~20-25 m diameter and ~3 m depth
- Small by lunar standards - similar in size to East Crater at Apollo 11 landing site
- Impact site - Cabeus A at lunar south pole, impact date Oct. 8

Lunar Swingby

Launch

Lunar Impact

ARTEMIS (2010)

- Acceleration, Reconnection, Turbulence and Electrodynamics of Moon's Interaction with Sun
- Moves 2 Earth-observing THEMIS satellites into lunar orbits
- ARTEMIS objectives:**
 - Study the lunar space environment, solar wind, magnetotail and lunar wake

GRAIL (2011)

- Gravity Recovery and Interior Laboratory, an SMD PI-led mission by Dr. Maria Zuber at MIT, managed by Discovery program at MSFC
- Based on GRACE on the Earth - twin spacecraft with mutual ranging
- GRAIL Objectives:**
 - Precisely map the gravity field of the Moon to recover information about the lunar interior structure and formation of the Moon

LADEE (2012)

- Lunar Atmosphere, Dust and Environment Explorer, Ames/GSFC project, managed by Lunar Quest Program at MSFC
- LADEE objectives:**
 - Characterize the fragile lunar atmosphere before it is perturbed by further human activity
 - Determine if Apollo astronaut sightings were Na glow or dust
 - Document the dust environment to help guide engineering for the outpost and future robotic missions

ILN Anchor Nodes (2018)

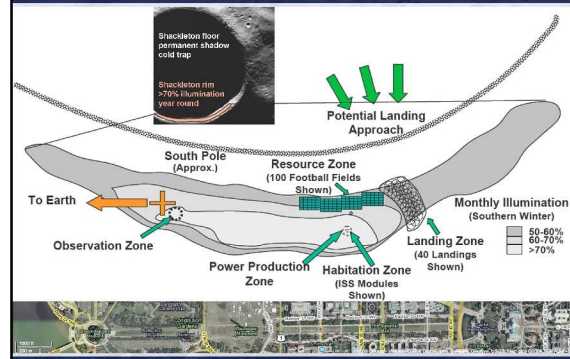
- + International Lunar Network— a geophysical network to accomplish high priority science, but difficult for any single agency to accomplish on its own
- + US and international landed missions, 2-4 US Landers planned, project at MSFC/APL, managed by Lunar Quest Program at MSFC

+ ILN Objectives:

- Understand the interior structure and composition of the moon
- Determine the thickness of the crust, mantle, and core
- Characterize the thermal state of the interior



Human landings (2020)



Summary

The Moon is a cornerstone for all rocky planets

- + The Moon is a **terrestrial** body, formed and evolved similarly to Earth, Mars, Mercury, Venus, and large asteroids
- + The Moon is a **differentiated** body, with a layered internal structure (crust, mantle, and core)
- + The Moon is a **cratered** body, preserving a record of bombardment history in the inner solar system
- + The Moon is an **active** body, experiencing moonquakes, releasing primordial heat, conducting electricity, sustaining bombardment, and trapping volatile molecules

Lunar robotic missions provide early science return to obtain important science and engineering objectives, rebuild a lunar science community, and keep our eyes on the Moon